APPLICATION OF QUENCHING TO POLYCRYSTALLINE METALLURGICAL SLAGS TO REDUCE COMMINUTION ENERGY AND INCREASE MINERAL LIBERATION

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PAPER NUMBER: IHTC16-22437

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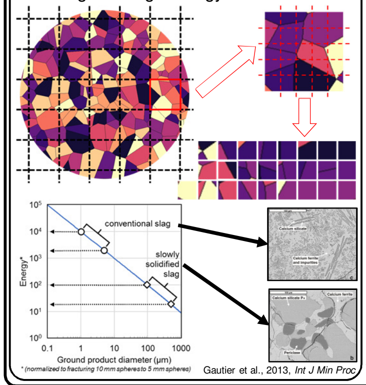
QUESTION: Can you liberate valuable minerals from heterogeneous iron and steel making slag by quenching?

CONCLUSION: YES! 40% liberation with a single quench. Interparticle grain size is the most important factor.

PROBLEM

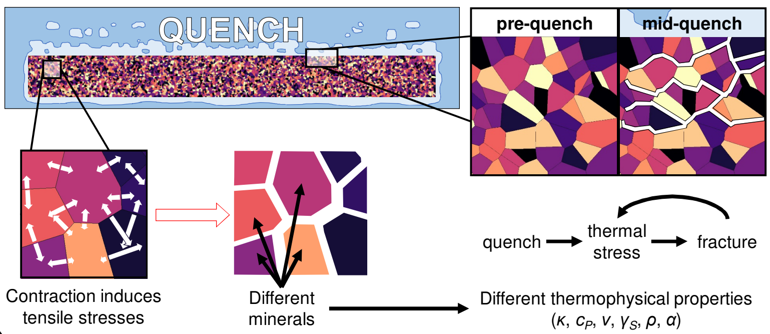
Grinding has large energy & low liberation



BACKGROUND

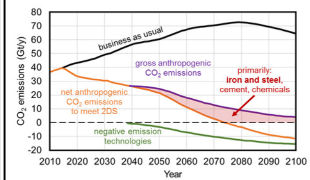
SOLUTION CONCEPT: Quench hot, solid slag in water (ΔT~900-1200 K).

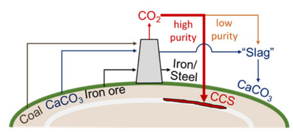
Isotropic thermal stress → grain boundary fractures → **liberation without energy penalty**



THE BIGGER PICTURE

to meet IEA 2DS…



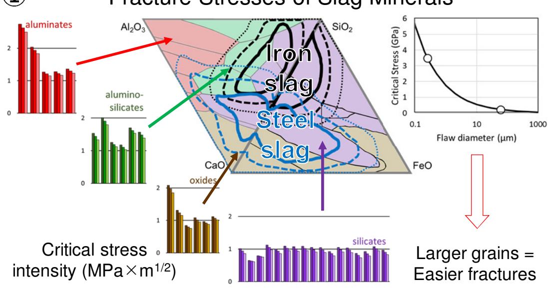


reduce 300-500 $MtCO_2$/y by 2050
CCS efficiency ↑, CCS cost ↓

RESULTS

(numbers link to Methods)

① Fracture Stresses of Slag Minerals

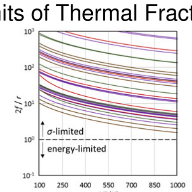


Critical stress intensity (MPa×$m^{1/2}$)

Larger grains = Easier fractures

Limits of Thermal Fracturing

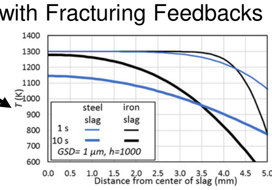
②

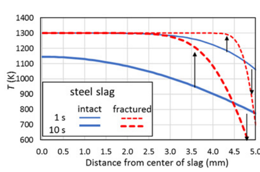


Sufficient energy for full liberation

Thermal Stress Evolution with Fracturing Feedbacks

③ ④ **Iron slag ≠ Steel slag**

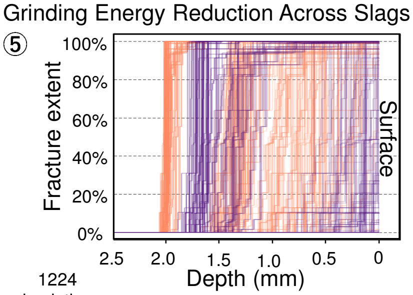




Fractures cause:
Shallow heat transfer ↑
Shallow fracturing ↑
Deep heat transfer ↓
Deep fracturing ↓

Grinding Energy Reduction Across Slags

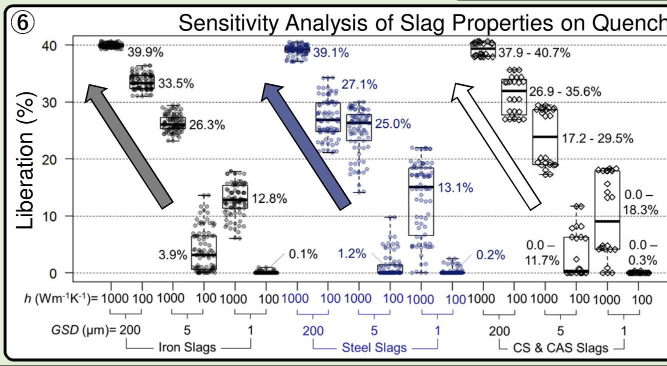
⑤



1224 simulations — h=1000 $Wm^{-1}K^{-1}$ — h=100 $Wm^{-1}K^{-1}$

Slag composition and quenching conditions matter!

⑥ Sensitivity Analysis of Slag Properties on Quenching Effectiveness



Single quench ≈ 40% liberation

Key takeaways:

- **Increase grain size**
- At conventional grain sizes:
  - > **Increase quench rate**
  - > Slag composition matters
  - > Fracturing feedbacks are significant

METHODS

① Calculate fracture stress & energy f(mineral, type, size)

Surface energy of intragranular fracture

$$\gamma_S = \frac{1}{2}\left[\left(\frac{1-2\nu}{3}\right)\left(N^{2/3}M_\alpha\right)\left(\frac{e^2}{4\pi\varepsilon_0}\right)\left(\frac{{R_0}^{n-1}}{n\times R_x^n}-\frac{1}{R_x}\right)\right]_{R_x=R_0}^{R_x=R_{limit}}$$

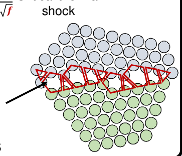
Surface energy of grain boundary fracture

$$\gamma_S = \frac{1}{2}\left[\left(\frac{1-2\nu}{3}\right)\left(N^{2/3}M_\alpha\right)\left(\frac{e^2}{4\pi\varepsilon_0}\right)\right] \times\left\{\left[f\left(\frac{{R_0}^{n-1}}{n\times R_x^n}-\frac{1}{R_x}\right)\right]_{R_x=R_0}^{R_x=R_{limit}}+\left[(1-f)\left(\frac{{R_0}^{n-1}}{n\times R_x^n}-\frac{1}{R_x}\right)\right]_{R_x=mR_0}^{R_x=R_{limit}}\right\}$$

$K_C = \frac{\sqrt{2E\gamma_s}}{\sqrt{1-\nu^2}}$ Critical stress intensity

Critical tensile stress $\sigma_C = \frac{K_C}{Y\sqrt{f}}$

$\Delta T_{C,x} = \frac{K_{C,x}}{E\beta Y\sqrt{f}}$ Critical thermal shock



Extended bond lengths and incomplete bonding weaken grain boundaries

② Determine if there is sufficient energy

Energetically limited 'radius' of thermal shock fracturing of a polycrystalline material

Sphere-to-voronoi increase in surface area

Increased surface roughness from high-loading rate fracture (e.g., thermal shock)

$$r = \frac{3\times 1.15\times 3.877\times BET}{\frac{\rho}{\gamma_{GB}}\int_{T_\infty}^{T_i} c_P(T)\,dT}$$

Available energy — Nano-scale surface roughness

$r > 2f$ → Energetically limited fracturing

$r < 2f$ → Stress limited fracturing

③ Analyze transient temperature and stress field

$$k\frac{\partial T(z,t)}{\partial z} = -h(T-T_\infty),\ at\ z=H$$

$$\frac{\partial^2 T(z,t)}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T(z,t)}{\partial t}$$

$$\zeta\tan\zeta = Bi = \frac{Hh}{k_{eff}}$$

solve for positive roots

$$\bar{T}(z,t) = -1 + 2\sum_{P=1}^{\infty}\left\{\left[\frac{\sin\varsigma_P\cos\left(\frac{\varsigma_P z}{H}\right)}{\varsigma_P+\sin\varsigma_P\cos\varsigma_P}\right]exp\left[-\frac{\varsigma_P^2\alpha t}{H^2}\right]\right\}$$

$$T(z,t) = \bar{T}(z,t)\Delta T + T_i$$

$$\bar{\sigma}(z,t) = -2\sum_{P=1}^{\infty}\left\{\left[\frac{\sin\varsigma_P}{\varsigma_P+\sin\varsigma_P\cos\varsigma_P}\right]\left[\cos\left(\frac{\varsigma_P z}{H}\right)-\left(\frac{\sin\varsigma_P}{\varsigma_P}\right)\right]exp\left[-\frac{\varsigma_P^2\alpha t}{H^2}\right]\right\}$$

$$\bar{E} = E(1-\nu^2)^{-1}$$

$$\bar{\beta} = \beta(1+\nu)$$

$$\sum_m\left[\varphi_m\frac{k_m-k_{bulk}}{k_m+2k_{bulk}}\right] = 0$$

heterogeneous solid & pores

$$k_{poly} = \left(\frac{1}{k_{bulk}}+\frac{n}{H}R_\lambda\right)^{-1}$$

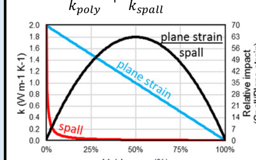
including grain boundaries

$$\sigma(z,t) = \bar{\sigma}(z,t)\bar{E}\bar{\beta}\Delta T$$

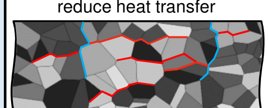
④ Account for feedbacks from fracturing

$$k_{spall} = \delta\left(\frac{k_{air\ @\ T_i}}{\delta}+\varepsilon k_B(T_z+T_{z+\delta})(T_z^2+T_{z+\delta}^2)\right)$$

$$k_{eff} = \frac{1}{\frac{\varphi_{poly}}{k_{poly}}+\frac{\varphi_{spall}}{k_{spall}}}$$

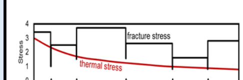


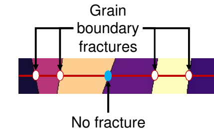
Spalling fractures reduce heat transfer



⑤ Calculate the grinding energy reduction

$$\int_0^H\sum_m\begin{cases}\sigma_{z,max} > \sigma_{C,GB} & \varphi_m\\ else & 0\end{cases}dz$$





⑥ Sensitivity analysis

grain size ? porosity
composition ? quench rate
radiation across voids

NOMENCLATURE: ***BET*** nanoscale surface roughness factor (-); c_P specific heat capacity (J kg^{-1} K^{-1}); ***E*** equilibrium tensile elastic modulus (Pa); ***f*** flaw radius (m); ***h*** convection coefficient (W m^{-2} K^{-1}); ***H*** ½ slag thickness (m); ***k*** thermal conductivity (W m^{-1} K^{-1}); k_B Stefan-Boltzmann constant (W m^{-2} K^{-4}); ***K*** stress intensity (Pa $m^{1/2}$); ***n*** number (-); ***r*** energy-limited fracture radius (m); R_λ Kapitza resistance (m^2 K W^{-1}); ***t*** time (s); ***Y*** flaw shape factor (-); ***α*** thermal diffusivity (m^2 s^{-1}); ***β*** volume expansion coefficient (K^{-1}); ***γ*** surface energy (J m^{-2}); ***δ*** spall thickness (m); ***ΔT*** thermal shock (K); ***ε*** emissivity (-); ***ς*** constant (-); ***ν*** Poisson's ratio (-); ***ρ*** density (kg m^{-3}); ***σ*** tensile stress (Pa); ***φ*** volume fraction (-)

IHTC-16 Beijing, China 2018